(12) EUROPEAN PATENT APPLICATION

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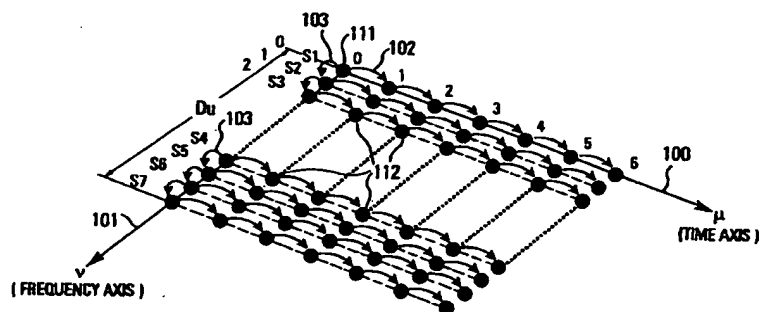Patent- und Rechtsanwälte
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(54) **Multicarrier communication method with time-frequency differential encoding**

(57) Method for transmitting blocks of data symbols via a transmission carrier divided into a plurality of parallel subcarriers spaced in frequency direction. The inventive method combines both differential encoding in frequency direction and differential encoding in time direction in order to combine the advantages of both modulation schemes. A first subset of data symbols, starting from a predefined primary subcarrier symbol position, is differentially encoded in frequency direction in order to provide primary subcarrier symbols for all subcarriers thereafter, the primary subcarrier symbols are differentially encoded in time direction with a second subset of the data symbols, thus providing secondary data symbols. Subcarrier vectors of subcarrier symbols are transformed into the time domain and transmitted via the transmission carrier.

Further, a data value describing the transmission quality of the transmission channel may be periodically received via a returning channel. And the first subset of data symbols for encoding in frequency direction may be selected in accordance with these channel conditions. The channel conditions may include information on the extent of time variance of the transmission channel.

FIG.2

EP 0 991 237 A1

Description

[0001]   The present invention relates to a method for transmitting data symbols associated with at least one communication channel between at least two devices of a communications system via a transmission carrier divided into a plurality of parallel subcarriers spaced in frequency direction.

[0002]   In today's communication networks, and in particular in wireless communication networks, a large number of subscribers needs to be serviced with limited transmission capacity, i.e., a limited bandwidth is available for providing services to a plurality of subscribers. Further, a transmission quality may be impaired by characteristics of the transmission medium or by external influences.

[0003]   A number of access schemes is known for placing a large number of communication channels onto a transmission medium. One of this access schemes is FDMA (Frequency-Division Multiple Access).

[0004]   In FDMA, signals from a plurality of users are assigned different frequencies of a frequency band of a transmission medium. Since each channel occupies its own frequency band or subcarrier, the communication signals may be transmitted simultaneously and mutually independent. Guard bands are maintained between adjacent signal spectra of subcarriers in order to minimize cross talk between different communication channels.

[0005]   In OFDM (Orthogonal Frequency Divisional Multiplexing), as for example described in "The Mobile Ccommunications Handbook", Jerry D. Gibson, CRC Press, Inc., 1996, ISBN 0-8493-8573-3, blocks of data symbols are transmitted in parallel by employing a large number of orthogonal subcarriers. OFDM thus parses the frequency-selective transmission channel into parallel and ideally independent transmission channels. The data symbols are usually associated with one single user. A frequency multiplexing may be implemented using the inverse discrete Fourier transform (IDFT) for data vectors in the modulator. A number of subcarriers, so-called virtual carriers, may be set to zero, in order to shape the power density spectrum appropriately.

[0006]   In OFDM, at first data symbols are mapped onto the subcarriers. A block of data is represented along the frequency axis. Such a block may be called frame. In a continuous data transmission frame after frame is transmitted, thus a two dimensional time-frequency plane of subcarrier symbols carrying the information to be transmitted is created. Then each subcarrier is modulated with a complex coefficient chosen according to a signal constellation. The subcarriers may have different complex coefficients. Thereafter, each subcarrier vector in frequency direction, comprising all carrier amplitudes at a particular instant in time, is transformed into the time domain, e.g., using the inverse discrete Fourier transform, resulting in a discrete time representation of the communication signal. This discrete time representation of the communication signal may then be transmitted via the transmission medium, e.g., a frequency band, using an ordinary pulse-amplitude modulation (PAM) technique. OFDM thus allows to transfrom a distortion of a signal, caused by a linear dispersive system (convolution of the transmitted signal with an impulse response of the transmission channel) into a multiplication of the subcarriers with the corresponding transfer function of the transmission channel.

[0007]   In OFDM, a certain number of samples from the transform output may be duplicated to form a so-called guard interval, wherein the duplicated samples may be placed in front of (cyclic prefix) or after (cyclic postfix) of the original samples. The guard interval allows to introduce a necessary cyclic characteristic of the signal.

[0008]   However, a time-dispersive and therefore frequency-selective channel distorts the transmission signal, and the receiver, after retransformation of the transmitted signal into the frequency domain, will obtain a noisy and distorted representation of the original subcarriers, i.e. subcarrier vectors in time direction (the subcarrier vectors have a defined length due to block transmission).

[0009]   To improve the quality of the received and demodulated signal, differentially encoded modulation schemes together with incoherent demodulation may advantageously be used, even though a loss in power efficiency for the digital transmission is connected with non-coherency. The use of differential encoding in OFDM is studied in "Principle of Modulation and Channel Coding for Digital Broadcasting for Mobile Subscribers", M. Alard and R. Lassalle, "EBU Review-Technical, No. 224, pp. 168-190, 1987." For differential encoding there is differentially encodable symbol alphabets (e.g., M-ary differential phase shift keying M-DPSK or M-ary differential amplitude and phase shift keying M-DAPSK) may be used.

[0010]   Accordingly, the transmitted information may be expressed as phase (and amplitude) variation from one subcarrier symbol to another subcarrier symbol, as it may be expressed as a multiplication of a previous subcarrier symbol with the information bearing symbol in order to obtain the next subcarrier symbol. Hence, the phase and the amplitude of the information bearing symbol expresses the phase difference and the amplitude ratio between subsequent data symbols.

[0011]   In OFDM, both directions for differential encoding, in time direction and frequency direction are feasible, as illustrated in Figs. 5 and 6.

[0012]   In Fig. 5, a differential encoding in time direction is illustrated. Fig. 5 shows a two dimensional time-frequency plane with plurality of subcarriers S1, S2, ... Sn is illustrated. The subcarriers are spaced in frequency direction along the frequency axis 101 with the frequency parameter v. Subsequent subcarrier symbols, illustrated by filled circles, of

a particular subcarrier are illustrated along a time axis 100 with the discrete time parameter μ.

[0013] As illustrated with arrows 102 in Fig. 5, each subcarrier symbol is obtained by processing a previous subcarrier symbol with a data symbol of the signal to be transmitted, i.e., the data symbols are differentially encoded. Thus, the transmitted information is contained in the transition between subsequent subcarrier symbols. As it becomes obvious with the direction of the arrows 102, the differential encoding is carried out in time direction, i.e. subsequent symbols of a particular subcarrier vector in time direction are obtained from a previous subcarrier symbol of the same subcarrier vector in time direction.

[0014] Fig. 6 shows an example for differential encoding in frequency direction. Again, a plurality of S1, S2 - Sn subcarriers are illustrated in the two dimensional time frequency plane, the subcarriers being spaced in frequency direction along the frequency axis 101 with the parameter v. In the example of Fig. 6, a subcarrier symbol of a particular subcarrier is now obtained by processing a subcarrier symbol from a neighboring subcarrier associated with the same instant in time, as it is indicated by arrows 103 in Fig. 6. Therefore, the information to be transmitted is now contained in the transitions between subcarrier symbols of adjacent subcarriers. As it becomes obvious with the direction of the arrows 103, the differential encoding is carried out in frequency direction.

[0015] Both techniques allow to improve transmission characteristics, however, differential encoding in time direction is still susceptible to carrier frequency offsets and differential encoding in frequency direction is still susceptible to frame synchronization errors and channel variations in frequency direction, as they inevitably occur in frequency-selective channels.

[0016] Further, both differential encoding schemes require considerable overhead, since for encoding in frequency direction the first symbol of each carrier must be spent as reference information and does not contain any useful information, and for differential encoding in time direction, an entire subcarrier vector in time direction must be spent as reference information and does usually not contain useful data-bearing information.

[0017] It is therefore object of the invention to provide a method for transmitting data symbols with improved transmission characteristics and at reduced overhead.

[0018] This objection of the invention is solved by a method for transmitting data symbols associated with at least one communication channel between at least two devices of a communications system via a transmission carrier divided into a plurality of parallel subcarriers spaced in frequency direction, comprising: differentially encoding at least one predefined primary subcarrier symbol of at least one subcarrier with a first subset of the data symbols in frequency direction, for generating primary subcarrier symbols for the remaining subcarriers; differentially encoding the primary subcarrier symbols with a second subset of the data symbols in time direction, for generating secondary subcarrier symbols; transforming each of a plurality of subcarrier vectors into the time domain, the subcarrier vectors being constituted by primary and secondary subcarrier symbols at predetermined instants in time; and transmitting the transformed subcarrier vectors, i.e., time domain samples, via the transmission carrier. That is, the time domain samples may be modulated onto the transmission carrier

[0019] In combining differential encoding in frequency direction and differential encoding in time direction in a multicarrier transmission, the invention allows to reduce transmission susceptibilities to time and frequency variations.

[0020] The invention further allows to considerably reduce a required overhead needed for bursty data transmission, since it is only required to provide a single primary or reference subcarrier symbol not containing any useful information. All other primary or reference symbols of all other subcarriers may be derived from this first subcarrier symbol and thus may already contain useful information.

[0021] According to an advantageous embodiment of the invention, the primary subcarrier symbols may constitute at least one subcarrier vector and thus provide reference information for encoding the individual subcarriers. Further, the secondary subcarrier symbols may constitute the remaining subcarrier vectors. Thus, at least one frequency encoded subcarrier vector may advantageously be provided for further reduction of a susceptibility to frequency variations. The higher the number of frequency encoded subcarrier vectors, the higher the robustness of the transmission with respect to time variations.

[0022] Advantageously, the steps of differential encoding and time direction and frequency direction may include multiplying a particular subcarrier symbol with a information bearing data symbol. The date symbol may be complex-valued.

[0023] In a further advantageous embodiment of the invention, data symbol blocks to be transmitted may include preamble information, and the first subset of data symbols may include this preamble information. Accordingly, preamble information may be advantageously used for referencing the individual subcarriers.

[0024] In case the number of primary symbols, e.g. the number of preamble symbols is smaller than the number of subcarriers, the step of differentially encoding in time direction may include using a primary subcarrier symbol located in a shortest distance in frequency direction with respect to a target subcarrier. Therefore, a subcarrier vector in time direction, which is not directly associated with a primary symbol, may still be encoded using a neighboring primary subcarrier symbols or primary subcarrier symbols located closest in frequency direction.

[0025] Further, if the number of primary symbols is smaller than a number of subcarriers, an interpolation between

existent primary subcarrier symbols may be employed before performing the step of differentially encoding in time direction. In this case, the invention advantageously allows to provide an estimation of a primary symbol of a subcarrier vector in time direction, thus allowing an encoding in time direction, if only a limited set of primary symbols is available.

[0026] Still further, a data value describing the transmission quality of the transmission channel may be periodically received via a returning channel. And the first subset of data symbols for encoding in frequency direction may be selected in accordance with these channel conditions. The channel conditions may include information on the extent of time variance of the transmission channel.

[0027] A transmission using OFDM (Orthogonal Frequency Division Multiplexing) may be advantageously employed.

[0028] The data symbols may include digital voice data of a cellular communication system, digital audio broadcasting data or digital video data, or a combination thereof.

[0029] Further advantageous embodiments of the invention are described in further dependent claims.

[0030] The invention may be best understood, if read together with the accompanying drawings, in which:

Fig. 1   shows a communication system employing the method according to the invention;

Fig. 2   shows an example of a plurality of parallel subcarriers in a two dimensional time-frequency plane without virtual subcarriers, the subcarrier symbols being differentially encoded in time direction and frequency direction in accordance with the invention;

Fig. 3   shows another example of a plurality of parallel subcarriers, including virtual subcarriers, in a two dimensional time-frequency plane, the subcarrier symbols being differentially encoded in time direction and frequency direction in accordance with the invention;

Fig. 4   shows an example of a plurality of parallel subcarriers including preamble information in a two dimensional time-frequency plane, the subcarrier symbols being differentially encoded in time direction and frequency direction in accordance with the invention;

Fig. 5   shows a known example for differential encoding in time direction; and

Fig. 6   shows a known example for differential encoding in time direction.

[0031] In the following, the invention will be described in detail, taking reference to the figures.

[0032] Fig. 1 shows a communication system employing the method according to the invention.

[0033] The communication system includes two communication devices 151, 156 for a communication between users, e.g., a voice, data, audio or video transmission. The communication system may be constituted by a broadcasting system.

[0034] In the example of Fig. 1, the communication device 151 transmits a data signal, e.g., a sequence of data symbols to an encoder 152. At the encoder, the data symbols from communication device 151 are arranged for a transmission via a transmission carrier divided into a plurality of parallel subcarriers spaced in frequency direction.

[0035] In particular, the encoder differentially encodes at least one predefined primary subcarrier symbol of at least one subcarrier (and a particular instant in time) with a first subset of the data symbols received from the communication device 151 in the frequency direction, for generating primary subcarrier symbols for the remaining subcarriers. Further, the encoder 152 differentially encodes the primary subcarrier reference symbols with a second subset of the data symbols from the communication device 151 in the time direction for generating secondary subcarrier symbols. Viewed in frequency direction, the thus generated grid of subcarrier symbols constitutes a plurality of subcarrier vectors.

[0036] The primary subcarrier symbol may generally be arbitrarily set, since only a phase (or amplitude) difference to the next symbol is of importance. However, for simplicity, a suitable value, e.g., 1 or 1+j, may be chosen and preset. A knowledge of this value in the receiver is not necessary. Thus, not the value but the position of the primary subcarrier symbol is of importance, for example, the number of the subcarrier v and the time instant μ. Thus, predefined primary subcarrier symbol in this context does not primarily refer to a value of the primary subcarrier symbol but to a position of the primary subcarrier symbol.

[0037] Thus, the encoder generates in a time-frequency plane a two dimensional grid of subcarrier symbols spaced in frequency direction, constituting subcarrier vectors in frequency direction, and spaced time direction, constituting subcarrier vectors in time direction. A subset of the two dimensional plane of the subcarrier symbols, according to the invention, is differentially encoded in frequency direction, another subset of the subcarrier symbols is differentially encoded in time direction. In general, any combination of differential encoding in time direction and differential encoding in frequency direction with generally arbitrary sequences of subcarrier symbols may be employed. Of course, the sequence of subcarrier symbols is to be known at the receiver.

[0038] The encoder then transforms each subcarrier vector in frequency direction (i.e., vectors of subcarrier symbols in frequency direction) into the time domain, each subcarrier vector in frequency direction being constituted by primary and/or secondary subcarrier symbols at a predetermined time instance. The transformation into the time domain may be carried out by a inverse discrete Fourier transform, as it is known in the art.

5   [0039] The subcarrier vectors transformed into the time domain are subsequently forwarded to a transmitter 153 for transmission, e.g., via an air interface. The signal forwarded to the transmitter may include duplicated symbols in front of the actual symbols (cyclic prefix) or after the actual symbols (cyclic postfix), constituting guard intervals. The transmitter 153 may, e.g., use an ordinary pulse-amplitude modulation (PAM) technique for transmitting the sequence of transformed subcarrier vectors via the transmission carrier.

10   [0040] The transmitted signal is received at a receiver 154, where the transformed subcarrier vectors are demodulated. Guard interval portions, if present, may also be from the time-domain signal removed at this point in time. The recovered time-domain vectors are then transmitted to a decoder 155, where the time-domain vectors are retransformed into the frequency domain, e.g., using a discrete Fourier transform. However, the subcarrier vectors are noisy and distorted (e.g., by a multiplicative factor). Subsequently, the decoder recovers the data signal by reversing the dif-

15   ferential encoding process in time and frequency direction of the encoder. Of course, the predefined position of the primary subcarrier symbol should be known at the receiver in this step.

[0041] The recovered data signal is subsequently transmitted to a receiving device 156.

[0042] The system of Fig. 1 may be used for transmission of a single signal between two users, or may be used for transmission of communication signals between a plurality of users. In this case, the individual sequences of data sym-

20   bols are combined in the encoder, as outlined above, such that a plurality of communication signals may be transmitted simultaneously within a unit, i.e., a frame. The data symbols to be transmitted may be arbitrarily arranged, i.e., distributed onto the time-frequency plane. For example, an individual communication signal may be placed on a subcarrier (i.e., constitute a subcarrier vector in time direction), a plurality of communication signals may be placed on a single subcarrier, or a single communication signal may be placed onto a plurality of subcarriers.

25   [0043] As outlined in the introductory section, the reception quality of a transmission signal transmitted, e.g., using OFDM, may be detonated by time and frequency shifts. Apart from channel distortion and additive noise at the receiver input, several additional impairments exist during a transmission and/or in the receiver.

[0044] A sampling frequency error may occur, so that the transmitter and the receiver have different frequency references for the channel sampling period. Hence, the modulation intervals differ in the transmitter and the receiver. This

30   impairment may be quantified by ξ_s in a normalized manner, i.e., it may be defined as the ratio of the sampling frequency error to the absolute sampling frequency and may typically be in the order of $\xi_s \approx 10^{-5} \dots 10^{-4}$.

[0045] Further, a frame synchronization error may occur due to the non-perfect knowledge of the absolute time in the receiver. Hence, the receiver assumes a signal start which is time shifted by some unknown time offset. The frame synchronization error may be quantified by ξ_t which gives the time offset normalized to the modulation interval.

35   [0046] Further, a carrier frequency error may occur, e.g., in the radio frequency oscillator, and the transmitter and receiver may not match in there absolute frequencies. This effect may be quantified by a normalized carrier frequency offset ξ_f which is defined as the ratio of the absolute frequency offset to the frequency spacing from one subcarrier to the next one.

[0047] The effects of each single synchronization parameter deviation usually results in an additional subcarrier inter-

40   ference as the parallel subcarriers may loose their mutual orthogonality. This interference may be interpreted as an additional noise and may be tolerated up to a certain degree. A second effect of frame synchronization errors, sampling frequency errors and carrier frequency offsets may be a (time-variant) phase rotation of the useful subcarrier components in the receiver.

[0048] In a coherent transmission scheme all of the above parameters may influence the quality of the received signal.

45   [0049] As an example, in OFDM, Du separate subcarriers having uniform frequency spacing in the available bandwidth be used. Hence, OFDM parses the frequency-selective transmission channel into Du parallel and ideally independent subcarriers.

[0050] As outlined before, the frequency multiplexing may be implemented by using the inverse discrete Fourier transform (IDFT) for D-ary (D≥Du) vectors in the encoder. A number of D-Du subcarriers - the so-called virtual carriers - is

50   set to zero, to shape the power density spectrum appropriately. The index v again denotes the discrete frequency index, which equivalently represents the subcarrier number. µ denotes the discrete time index.

[0051] In OFDM, at first, binary data is mapped onto the Du subcarriers. Thereby, subcarrier symbol v,µ is modulated with a complex coefficient $A_{\mu,v}$ chosen according to a signal constellation. However, not all Du active subcarriers need to employ the same complex-valued signal set.

55   [0052] The subcarrier vector $[A_{\mu,0}, \dots , A_{\mu,D-1}]$ comprising all subcarrier symbols at time instant µ is transformed into the time domain, using a D-point IDFT. This results in the discrete time representation of the transmit signal in the µth block which consists of exactly D sample values.

[0053] A total number of Ds - D samples from the transform output is duplicated to form the guard interval, where Ds

≥ D is the overall number of samples associated with one subcarrier vector.

[0054]   The arrangement of the duplicated samples can be done such that all samples are placed in front of (cyclic prefix) or after (cyclic postfix) the original D samples. A mixture of both is possible, too.

[0055]   Finally, the Ds samples of time interval μ may be transmitted using an ordinary PAM (pulse amplitude modulation).

[0056]   Assuming a frequency-selective but time-invariant channel, and assuming rather small parameter values ξ_s, ξ_f and ξ_t, the received subcarrier amplitude $Y_{\mu,\nu}$ in subcarrier ν at a time instant μ may then be written as

$$Y_{\mu,\nu} \approx e^{+j\frac{2\pi}{D}\left[\xi_f\left(\frac{D-1}{2}+D_s\mu\right)+\left(\xi_t+\frac{D-1}{2}\xi_s+D_s\xi_s\mu\right)\nu\right]} \cdot H[\nu] \cdot A_{\mu,\nu}+\text{noise and interference} \qquad (1)$$

where the subcarrier-dependent factor H [ν] represents the discrete channel transfer function at the frequency of subcarrier ν. H [ν] is a complex-valued variable and in most cases H [ν + 1] is approximately H [ν], so that there is sufficient coherence between the channel influence in adjacent subcarriers. Further, equation (1) exhibits phase rotations (leftmost factor in Eq. (1)) which consist of static and time-variant components. For the latter, phase terms are encountered, which are linearly increasing with the subcarrier number ν (frequency), some rise with the time μ and some are linear in $\mu\nu$.

[0057]   Equation (1) represents the output signal of the receiver 154 after retransformation into the frequency domain (e.g., using a discrete Fourier Transform), on which the demodulator 155 must base its decision upon. In a so-called coherent transmission scheme, the information is contained in the transmitted absolute subcarrier amplitude $A_{\mu,\nu}$, as outlined above, and a large number of parameters is required to be known or estimated in the receiver to allow a proper coherent demodulation.

[0058]   Especially phase rotating influences have to be suppressed or tracked and the channel transfer function is required to be estimated to recover the phase, and, if required, the amplitude of $A_{\mu,\nu}$. By the use of differentially encoded modulation with incoherent reception it may be achieved that some of the phase rotations cancel out in the decision variable so that an increasing tolerance to some synchronization errors is obtained.

[0059]   However, differentially encoding in time direction is mainly aimed at reducing effects induced frequency selectivity, whereas differentially encoding in frequency direction is mainly aimed at reducing time induced effects, as outlined in the introductory portion of the application.

[0060]   In order to combine the benefits of differential encoding in time direction and frequency direction, with respect to the sensitivity to synchronization deviations in carrier frequency, symbol timing and frame timing, differential encoding in time direction and frequency direction is combined for the same block of data symbols. The combination of differential encoding and time direction and frequency direction within the same data block will be described in detail with respect to Fig. 2.

[0061]   Fig. 2. shows an example of a plurality of parallel subcarriers S1-Sn, corresponding to amplitudes $A_{\mu,0}$,..... . $A_{\mu,D-1}$, in a two dimensional time-frequency plane, the subcarrier symbols being differentially encoded in time direction and frequency direction in accordance with the invention. The individual subcarriers are spaced in frequency direction along the frequency axis 101 with the frequency parameter ν, and extend along the time axis 100 with the time parameter μ.

[0062]   As illustrated in Fig. 2 with arrows 102 and arrows 103, one predefined primary subcarrier symbol position ill assigned to the first subcarrier S1, is differentially encoded in frequency direction with a first subset of the data symbols to be transmitted, for generating primary subcarrier symbols for the remaining subcarriers S2, . .., Sn spaced in frequency direction. Accordingly, using a first data symbol, the predetermined primary subcarrier symbol at location $\nu=0$; $\mu=0$ is differentially encoded (in frequency direction) into the primary subcarrier symbol at location $\nu=1$; $\mu=0$, this symbol is differentially encoded, using a second data symbol, into the primary subcarrier symbol at location $\nu=2$, $\mu=0$, etc.

[0063]   The thus generated primary subcarrier symbols are differentially encoded in time direction with a second subset of the data symbols, thus generating secondary subcarrier symbols. Therefore, the predetermined primary subcarrier symbol at location $\nu=0$, $\mu=0$ is differentially encoded into the subcarrier symbol at location $\nu=0$; $\mu=1$, this symbol is differentially encoded (in time direction), using a second data symbol, into the subcarrier symbol at location $\nu=0$, $\mu=2$, etc., Further, the primary subcarrier symbol at location $\nu=1$, $\mu=0$ is encoded into the subcarrier symbol at location $\nu=1$, $\mu=1$, etc.

[0064]   Of course, any other sequence of symbols in the above two encoding directions is possible.

[0065]   The thus generated subcarrier vectors, vectors of subcarrier symbols in frequency direction, may then be transformed into the time domain and transmitted.

[0066]   In the example of Fig. 2, the steps of differential encoding in frequency direction and time direction start from a single predefined primary subcarrier symbol position 111. Here, a first subset of data symbols is encoded in frequency directions starting from the primary subcarrier symbol 111. This step provides primary subcarrier symbols for

all subcarriers. Starting from the now obtained primary subcarrier symbols a second set of data symbols is encoded in time direction, as illustrated by the arrows 102. This step generates secondary subcarrier symbols 112. Of course, the subcarrier symbols do not have to be encoded in the above order.

[0067] In the example of Fig. 2, the first subcarrier vector in frequency direction, at time instant $\mu = 0$, is generated by encoding in frequency direction. All other subcarrier vectors are generated by encoding in time direction. However, the invention is not limited to encoding the first subcarrier vector in frequency direction for providing reference symbols, in principal any other subcarrier vector may be encoded in frequency direction.

[0068] According to the invention, by using a combination of differentially encoding data symbols in time direction and frequency direction, the advantages of the two differentially encoded modulations differentially encoded modulation schemes are combined. Performing part of the encoding in frequency direction allows to reduce the influence of time variations, and further, the encoding of another subset of the data symbols in time direction allows to reduce the influence of frequency variations, as outlined in the following.

[0069] The differential encoding in time direction is performed along the time axis denoted by the parameter μ, e.g. according to

$$A_{\mu+1,v} = A_{\mu,v} \cdot I_{\mu,v} \qquad \forall v \in [0, D-1], \forall \mu \qquad (2)$$

[0070] According to Eq. (2), the subcarrier transitions from subcarrier amplitude $A_{\mu,v}$ to $A_{\mu+1,v}$ are differentially encoded in time direction with the complex-valued information amplitude $I_{\mu,v}$. The complex information amplitude $I_{\mu,v}$ may be a data symbol of a signal to be transmitted, or may be derived from one or more of the data symbols. As seen in Fig. 2 the filled circles represent the grid of absolute amplitudes $A_{\mu,v}$ in the time-frequency plane and the arrows 103 denote the multiplication with the respective $I_{\mu,v}$.

[0071] The decision variable for a differential demodulation in time direction, as for example performed by the decoder 155 may be written as

$$Y_{\mu,v}^* Y_{\mu+1,v} \approx e^{+j\frac{2\pi}{D}[D_s\xi_f + D_s\xi_s v]} \cdot |H[v]| \cdot |A_{\mu,v}|^2 \cdot I_{\mu,v} + \text{noise and interference} \qquad (3)$$

where * denotes a complex conjugation. Eq. (3) is derived by incorporating equation (1) and using the identity $A_{\mu,v}^* A_{\mu+1,v} = |A_{\mu,v}|^2 I_{\mu,v}$. Here, the factor $I_{\mu,v}$ may represent the useful (phase) information according to the differentially encoded modulation. It is noted, that a differential encoding with respect to the amplitude is also possible.

[0072] As can be seen from equation (3), the differentially encoded signal in time direction is robust against time offsets, as ξ_t disappears. However, it is still susceptible to carrier frequency offsets ξ_f.

[0073] The differential encoding in frequency direction of a subset of data symbols, as shown in Fig. 6, is appropriate for rapidly time-varying channel.

[0074] The differential encoding in frequency direction may be performed along the frequency axis denoted μ according to

$$A_{\mu,v+1} = A_{\mu,v} \cdot I_{\mu,v} \qquad \forall v \in [0, D-2], \forall \mu \qquad (4)$$

[0075] Hence, the subcarrier transitions from subcarrier amplitude $A_{\mu,v}$ to $A_{\mu,v+1}$ are differentially encoded in frequency direction with the preferably complex-valued information amplitude $I_{\mu,v}$. Of course, the information amplitude derived from the data symbol may be real valued, too.

[0076] The decision variable for differential demodulation in frequency-direction, as i.e. performed by the decoder 155 may be written as

$$Y_{\mu,v}^* Y_{\mu,v+1} \approx e^{+j\frac{2\pi}{D}\left[\xi_t + \frac{D-1}{2}\xi_s + D_s\xi_s\mu\right]} \cdot H^*[v] \cdot H[v+1] \cdot |A_{\mu,v}|^2 \cdot I_{\mu,v} + \text{noise and interference} \qquad (5)$$

[0077] Eq. (5) incorporates Eq. (1) and uses the identity

$$A_{\mu,v}^* A_{\mu,v+1} = |A_{\mu,v}|^2 I_{\mu,v}.$$

[0078] There are two multiplicative distortions which introduce a phase bias to the demodulation variable. A time offset has the effect of a constant phase angle $\xi_t 2\pi/D$. If the number of subcarriers N is sufficiently large and the sampling offset ξ_t is not significantly larger than a few percent of N, this phase bias due to the time offset will be small and negli-

gible. Secondly, the product of the discrete channel transfer functions H*[v] H[v+1] will itself produce a phase offset, which depends on the channel variations in frequency direction.

[0079] The differentially encoded data symbols in frequency direction can therefore be relatively robust against carrier frequency offset as the phase rotation due to ξ_l is canceled. But differential encoding is susceptible to frame synchronization errors and channel variations in frequency direction like they inevitably occur in frequency-selective channels.

[0080] However, since a subset of data symbols, e.g., of a data block of a predefined length, is encoded in frequency direction, and a second subset of data symbols is encoded in time direction, as outlined above, the susceptibility of the jointly modulated data symbols to frequency and time parameters can be reduced by adapting the major direction of encoding according to the channel behaviour.

[0081] Further, it is not any longer necessary to spend a full subcarrier vector for reference for the encoding, it is merely necessary to provide a single primary subcarrier symbol as a reference for a first subcarrier.

[0082] Hence, the invention allows a substantial reduction of a transmission overhead, especially for a transmission of smaller data blocks, since a minimum of only one primary subcarrier symbol not carrying any information is needed. All other subcarrier symbols may be derived from this primary subcarrier symbol. In the prior art, for differential encoding in frequency direction, and for differential encoding in time direction, a complete subcarrier vector and subcarrier, respectively, are not information carrying.

[0083] Fig. 3 shows an example of Du parallel subcarriers S1-Sn in the two dimensional time-frequency plane (μ,v), the subcarrier symbols being differentially encoded in time direction and frequency direction in accordance with the invention. Again, the subcarriers are spaced in frequency direction. As illustrated by empty circles in Fig. 3, a number of D - Du subcarrier vectors are set to zero, in order to shape the power spectrum appropriately.

[0084] In Fig. 3, now two primary subcarrier symbols 111, 113 are defined as initial "seeds" for the differential encoding in time and frequency direction. The encoding in time and frequency direction is performed as before, e.g., as it was outlined with respect to Fig. 2. Starting from a predefined primary subcarrier symbol 111, associated with subcarrier S1, a subset of data symbols is encoded in frequency direction for generating primary subcarrier symbols of the remaining subcarriers. Similarly, starting from a predefined primary subcarrier symbol 113 of the first subcarrier S1, data symbols are encoded in frequency direction in order to provide further primary symbols for the remaining subcarriers.

[0085] Following, starting from the two sets of primary subcarrier symbols, a further subset of data symbols is encoded in time direction, as before.

[0086] Of course, apart from providing a single primary subcarrier vector in the embodiment of Fig. 1, and providing two primary subcarrier vectors according to the embodiment of Fig. 2, a larger number or other combinations of primary subcarrier symbols may be provided. For example, only part of a subcarrier vector may be encoded in frequency direction for providing primary subcarrier symbols.

[0087] The generation of primary subcarrier symbols by encoding data symbols in frequency direction may also be dynamically adjusted in order to adapt the encoding scheme to transmission conditions on the transmission carrier. Via a return channel information about the transmission conditions of the transmission carrier may be transmitted back to the encoder 152, such that at the encoder an appropriate combination of encoding in frequency direction and time direction may be employed. For example, the data value transmitted via the return channel may describe the extent of time variance of the transmission carrier. Accordingly, in case of a large time variance, the encoder may for example increase the number of frequency encoded data symbols in order to reduce the negative influence of a time variant transmission carrier.

[0088] In the previous examples it was assumed that the data symbols to be transmitted are not equipped with the preamble sequence for synchronization or for any other purposes.

[0089] Fig. 4 now shows an example for combining differential encoding in time direction and frequency direction in case the data symbols contain preamble information. The preamble, as, e.g., in OFDM, may be used for synchronization purposes (e.g., frame and frequency synchronization) and may also partially carry information.

[0090] According to the invention it is possible to use the preamble information as the first subset of data symbols for differential encoding in frequency direction. However, in efficiently dimensioned preambles the number of symbols of the preamble may not be equal to the number of subcarriers and in most cases the number of symbols of the preamble will be smaller than the number of subcarriers. Accordingly, when encoding preamble data symbols in frequency direction, in order to generate primary subcarrier symbols for all subcarriers, the number of generated subcarrier symbols will be smaller than the number of subcarriers of the subsequent OFDM symbols. Thus, the step of differentially encoding the second subset of data symbols in time direction may include using a primary subcarrier symbol located in a shortest distance in frequency direction with respect to a target subcarrier in order to solve the problem of a missing explicit primary subcarrier symbol, i.e., missing perfect reference.

[0091] Further, in case the number of primary symbols is smaller than a number of subcarriers, the step of differentially encoding the second subset of data symbols in frequency and time direction may include interpolating primary subcarrier symbols in order to overcome problems associated with missing primary subcarrier symbols. This step may be executed in the transmitter and/or receiver.

[0092]   Fig. 3 illustrates an example, where the number of primary subcarrier symbols generated by encoding, e.g., preamble information, in frequency direction is only half the number of subcarriers. In this case, each primary subcarrier symbol is used as a reference for two subcarriers, by choosing the primary subcarrier symbol located closest in frequency direction to a target subcarrier. For example, the primary subcarrier symbol of the third subcarrier S3 is used as a reference not only for the third subcarrier S3 but also for the fourth subcarrier S4.

[0093]   As it is obvious with the above description, the invention allows a minimization of overhead for reference symbol signaling, since only a small, in the best case only one primary subcarrier symbol is needed for the encoding process. Further, the invention provides an efficient and advantageous use of both differential encoding schemes in time and frequency direction for reducing the influence of time and frequency variations.

[0094]   The invention may be applied to any multicarrier system, such as discrete multitone, e.g., in a so called X-DSL technique and OFDM (Orthogonal Frequency Division Multiplexing).

[0095]   Data transmitted using the inventive method may incorporate a plurality of communication channel signals, may include digital voice data of a cellular communication system, digital audio broadcasting data, digital video data or a combination thereof. The invention may be employed in communication systems, in particular cellular communication systems and broadcasting systems.

Claims

1.   Method for transmitting data symbols associated with at least one communication channel between at least two devices of a communications system via a transmission carrier divided into a plurality of parallel subcarriers spaced in frequency direction, comprising:

differentially encoding at least one predefined primary subcarrier symbol of at least one subcarrier with a first subset of the data symbols in frequency direction, for generating primary subcarrier symbols for the remaining subcarriers;

differentially encoding the primary subcarrier symbols with a second subset of the data symbols in time direction, for generating secondary subcarrier symbols;

transforming each of a plurality of subcarrier vectors into the time domain, the subcarrier vectors being constituted by primary and secondary subcarrier symbols at predetermined instants in time; and

transmitting the transformed subcarrier vectors via the transmission carrier.

2.   Method according to claim 1, characterized in that the data symbols are transmitted in blocks of a predefined length.

3.   Method according to claims 1 or 2, characterized in that

the primary subcarrier symbols constitutes at least one subcarrier vector; and

the secondary subcarrier symbols constitute the remaining subcarrier vectors.

4.   Method according to one of the preceding claims, characterized in that the steps of differential encoding in time and frequency direction include multiplying a subcarrier symbol with a data symbol.

5.   Method according to one of the preceding claims, characterized in that the data symbols are complex valued.

6.   Method according to one of the preceding claims, characterized in that the data sequence includes preamble information and the first subset of data symbols includes this preamble information.

7.   Method according to claim 6, characterized in that, if the number of primary symbols is smaller than the number of subcarriers, the step of differentially encoding the second subset of data symbols in time direction includes using a primary subcarrier symbol located in a shortest distance in frequency direction with respect to a target subcarrier.

8.   Method according to claim 6, characterized in that, if the number of primary symbols is smaller than the number of subcarriers, the step of differentially encoding the second subset of data symbols in time direction includes interpolating primary subcarrier symbols.

9. Method according to one of the preceding claims, characterized by

    periodically receiving a data value via a return channel describing the transmission quality of the transmission channel; and

    selecting the first subset of data symbols for encoding in frequency direction in accordance with the transmission quality.

10. Method according to claim 9, characterized in that the data value includes information on the extent of time variance of the transmission channel.

11. Method according to one of the preceding claims, characterized in that the transmission includes OFDM (Orthogonal Frequency Division Multiplexing).

12. Method according to one of the preceding claims, characterized in that the data sequences include at least one of the group consisting of:

    digital voice data of a cellular communications system;

    digital audio broadcasting data; and

    digital video data;

13. Communications device using the method according to one of the claims 1 to 12.

14. Broadcasting system using the method according to one of the claims 1 to 12.
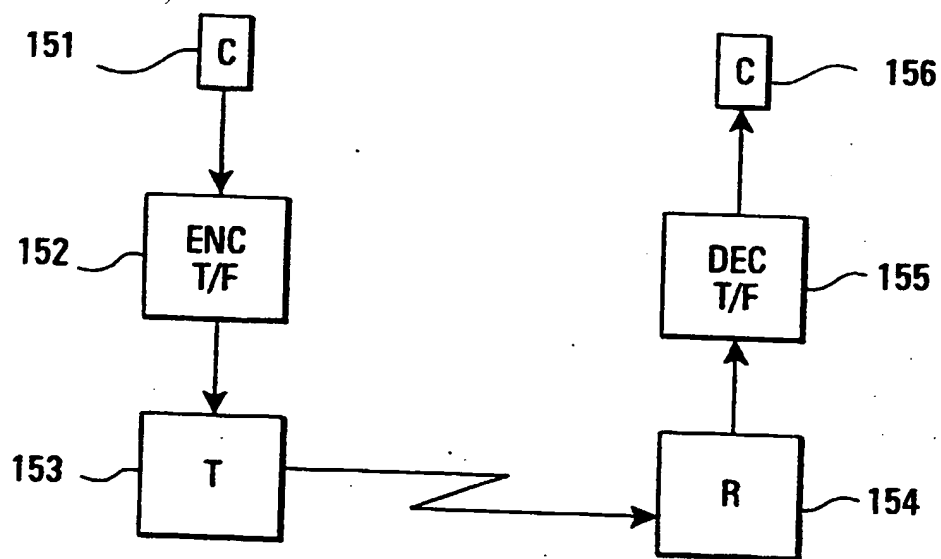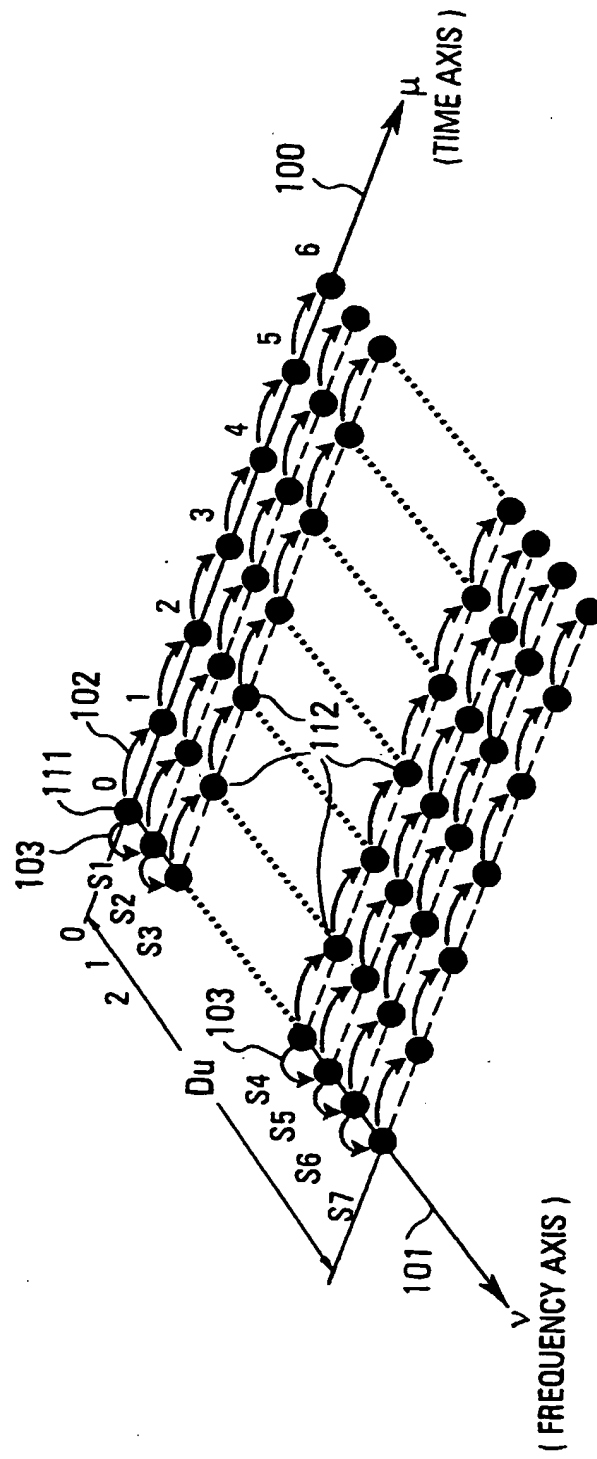
FIG.1

```
151 ⌇  [C]                          [C] ⌇ 156
         │                            ↑
         ↓                            │
152 ⌇  ┌─────┐              ┌─────┐
       │ ENC │              │ DEC │ ⌇ 155
       │ T/F │              │ T/F │
       └─────┘              └─────┘
         │                    ↑
         ↓                    │
153 ⌇  ┌─────┐              ┌─────┐
       │  T  │────────⌇────→│  R  │ ⌇ 154
       └─────┘              └─────┘
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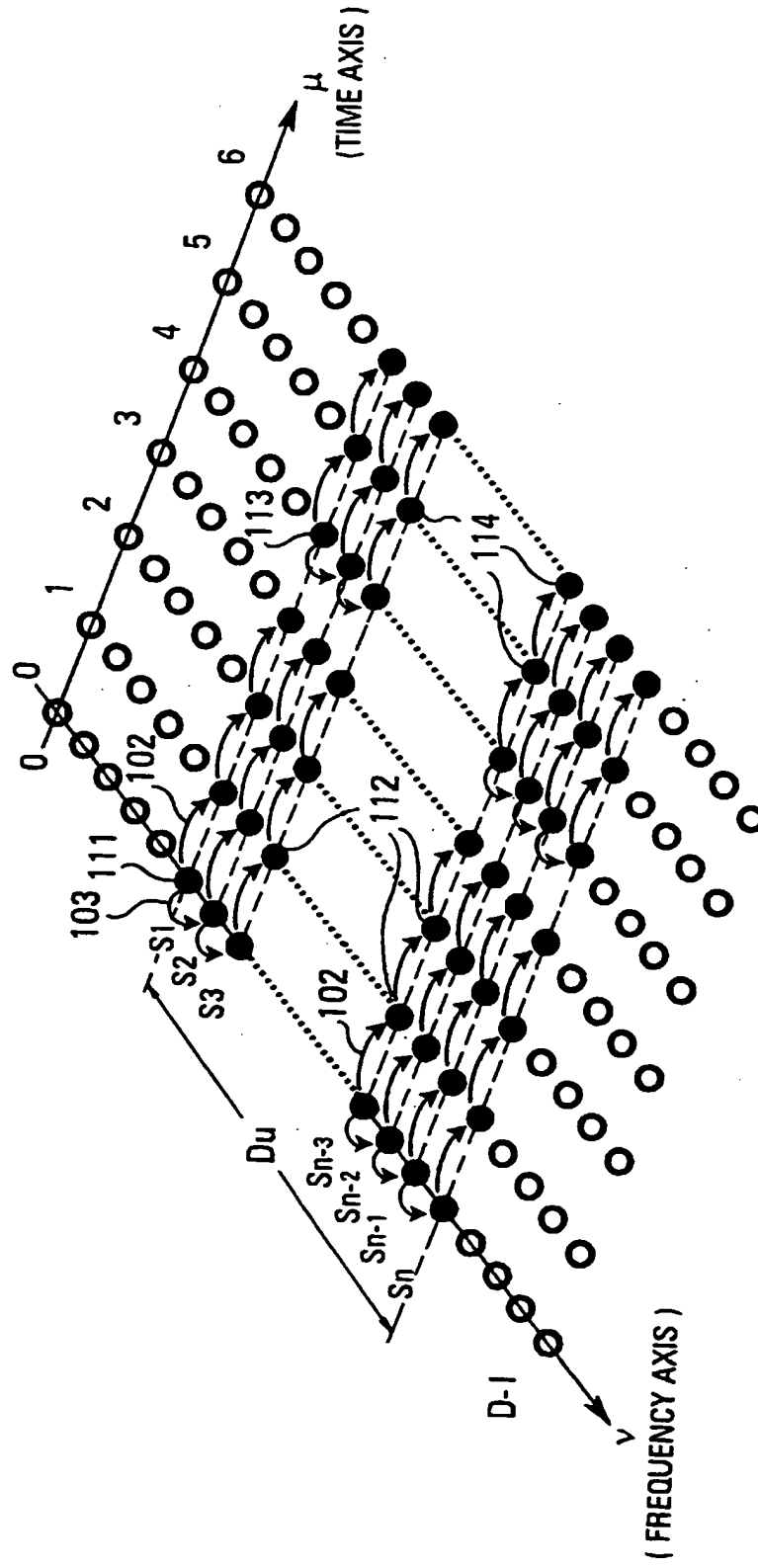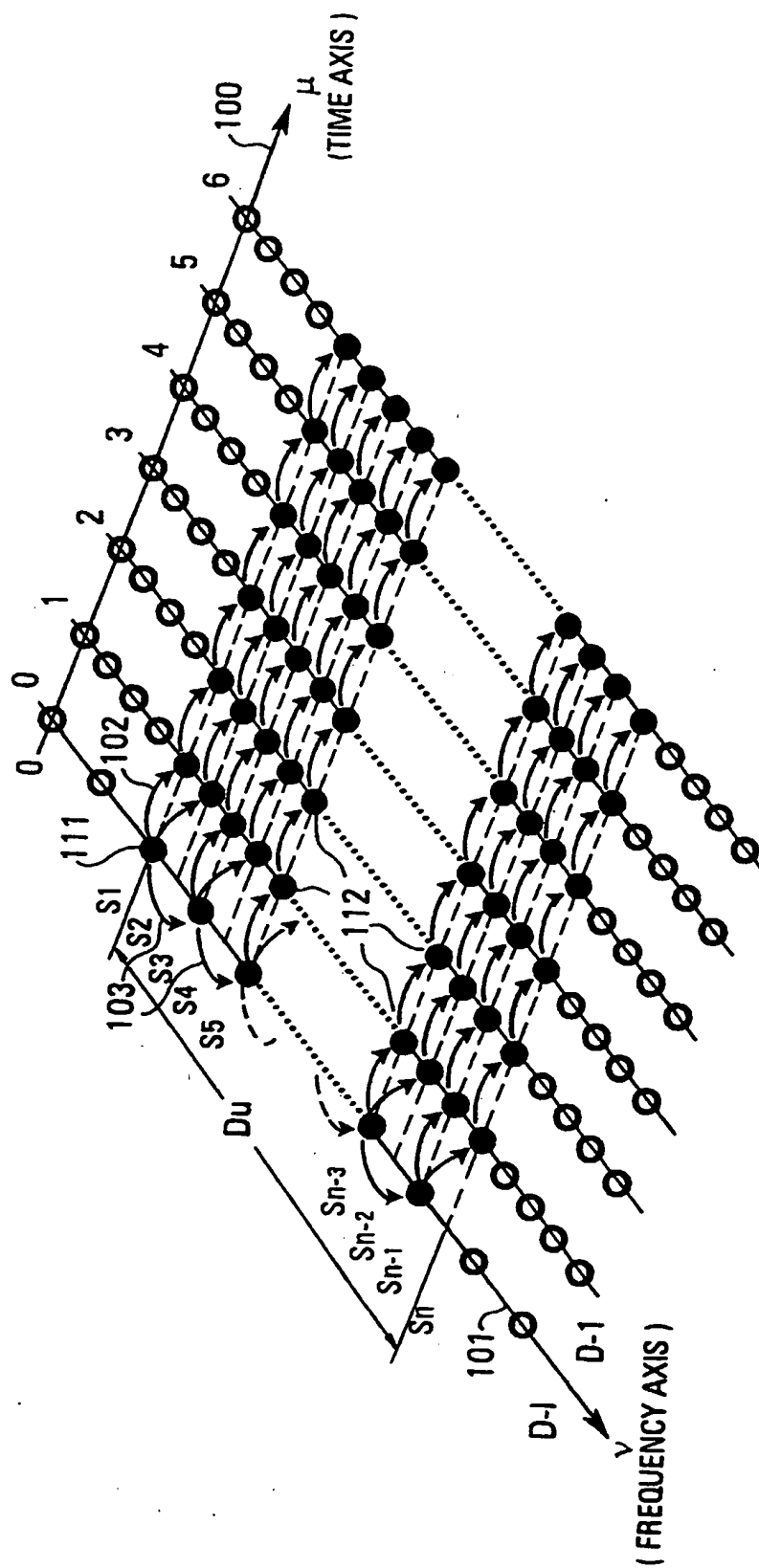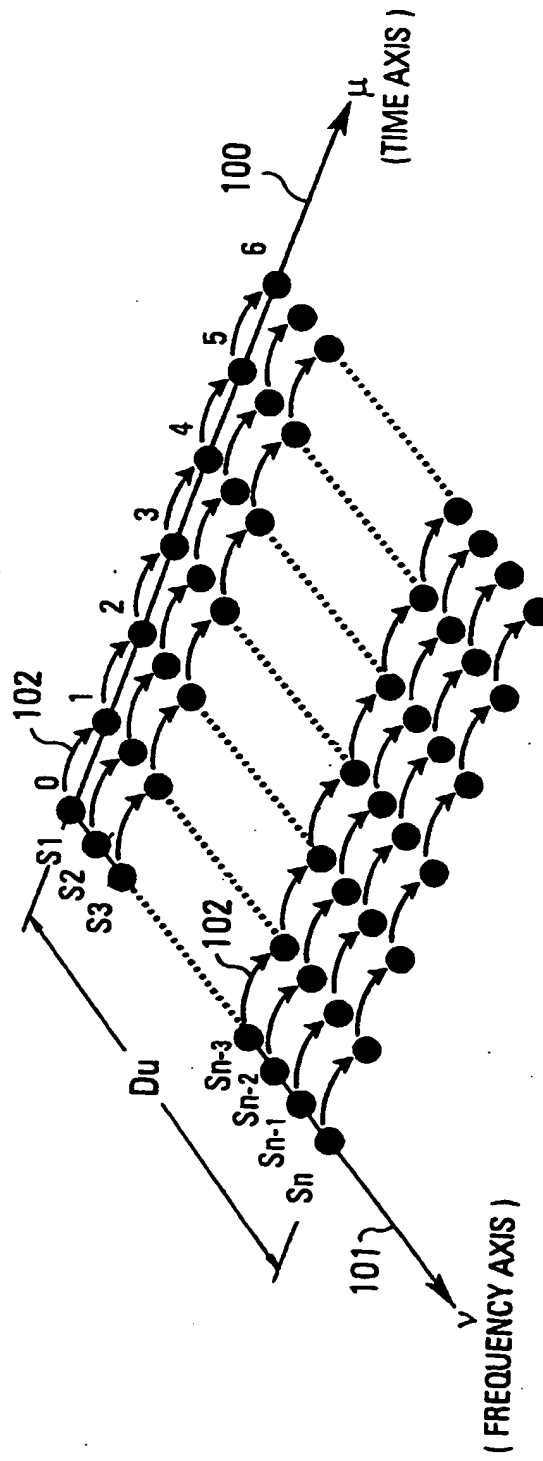
FIG.2
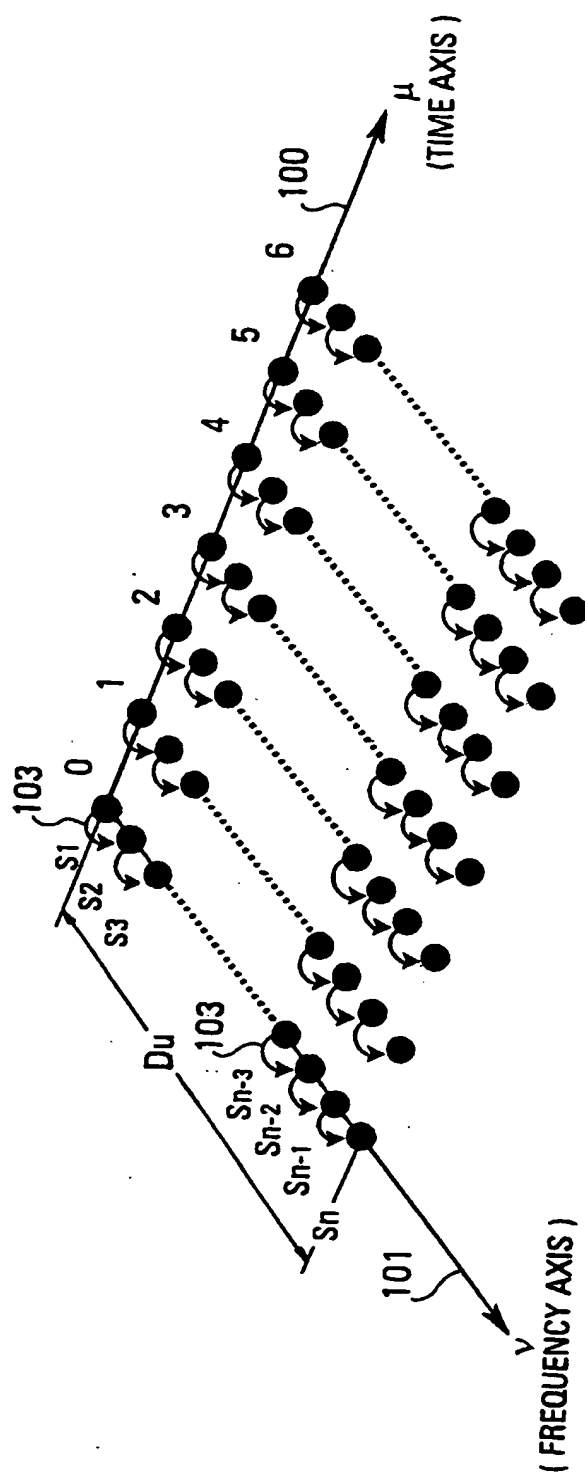
FIG.3

FIG.4

FIG.5

FIG.6

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 98 11 8471

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X	EP 0 752 779 A (NOKIA MOBILE PHONES LTD ;NOKIA TELECOMMUNICATIONS OY (FI)) 8 January 1997 * column 7, line 8 - column 9, line 22 * * figures 3,4B * * claims 1,2 *	1-6, 11-14	H04L27/26 H04L1/12
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H04L

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	1 March 1999	De Riccardis, F

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